Team adds to quantum computing toolkit with mixed-atom logic operations

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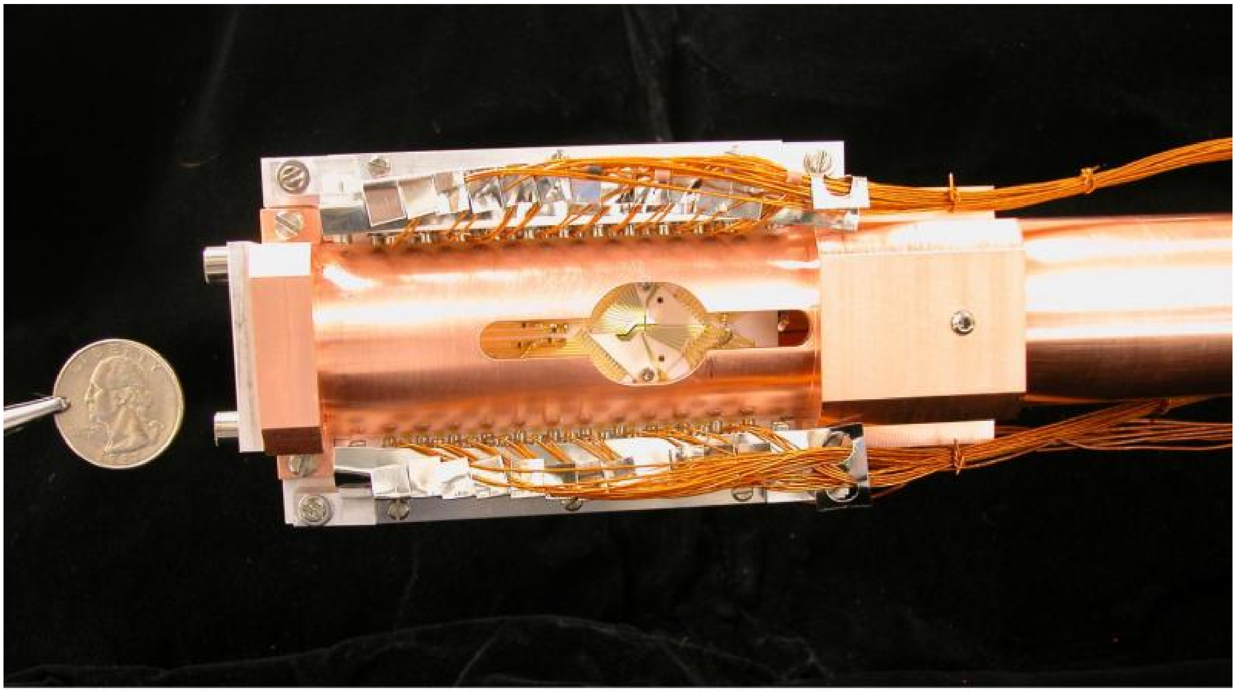

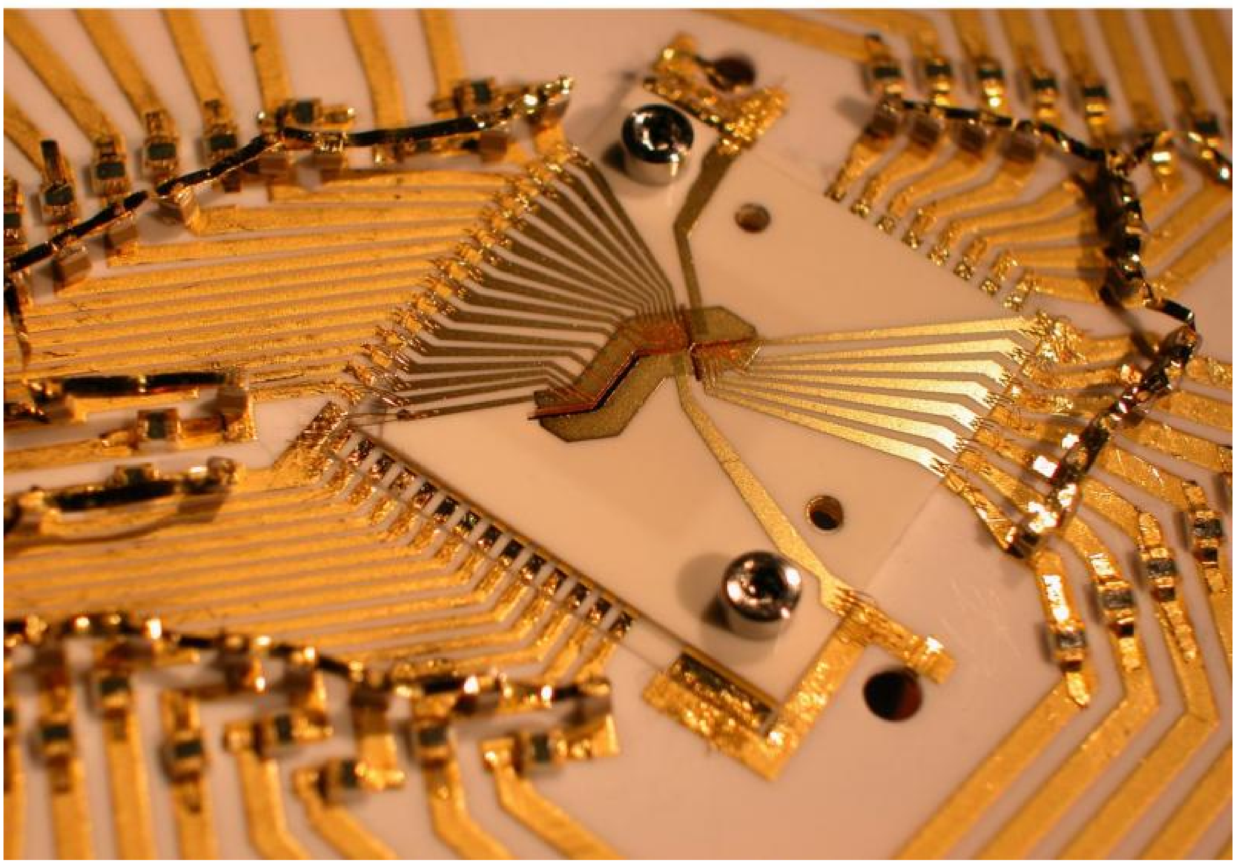

An ion trap used in NIST quantum computing experiments demonstrating logic operations with two different types of ions (charged atoms). One magnesium ion and one beryllium ion are trapped 4 micrometers apart near the cross-shaped opening at the center of both photos.The larger-scale photo shows the gold-on-alumina trap inside a case that protects against electrical interference. Credit: Blakestad/NIST

Physicists at the National Institute of Standards and Technology (NIST) have added to their collection of ingredients for future quantum computers by performing logic operations—basic computing steps—with two atoms of different elements. This hybrid design could be an advantage in large computers and networks based on quantum physics.

The NIST experiment, described in the Dec. 17 issue of *Nature*, manipulated one magnesium and one beryllium ion (charged atom) confined in a custom trap (see photo). The scientists used two sets of laser beams to entangle the two ions—establishing a special quantum link between their properties—and to perform two types of logic operations, a controlled NOT (CNOT) gate and a SWAP gate. The same issue of *Nature* describes similar work with two forms of calcium ions performed at the University of Oxford.

"Hybrid quantum computers allow the unique advantages of different types of quantum systems to be exploited together in a single platform," said lead author Ting Rei Tan. "Many research groups are pursuing this general approach. Each ion species is unique, and certain ones are better suited for certain tasks such as memory storage, while others are more suited to provide interconnects for data transfer between remote systems."

Gates are used to build circuits or programs. As in classical computing, a quantum bit (qubit) can have a value of 0 or 1. But unlike classical bits, a qubit can also be in a "superposition" of both 0 and 1 values at the same time. In the NIST experiment, the qubits are based on the ions' spin directions (spin up is 1 and spin down is 0). A CNOT gate flips the second (target) qubit if the first (control) qubit is a 1; if it is a 0, the target bit is unchanged. If the control qubit is in a superposition, the ions become entangled. A SWAP gate interchanges the qubit states, including superpositions.

The two types of ions vary in their response to light, so lasers can be tuned to manipulate one without disturbing the other. This minimizes interference. But getting the whole setup to operate coherently was a challenge. The researchers developed a technique to track and stabilize the laser beam phases, that is, the exact positions of the undulating light waves.

"For the logic gate to work, the phase has to be at the correct values. Also, these phases have to be stable, so we can apply the same condition over many repetitions," Tan said.

If they can be built, quantum computers could solve problems now considered intractable, such as breaking today's best data encryption codes. The same NIST group has demonstrated many other building blocks for quantum computers based on trapped ions. For example, the group demonstrated the first quantum logic gate (a CNOT gate) on individual qubits in 1995 using a single beryllium ion.

NIST's latest techniques provide a complete or "universal" set of quantum gates—meaning they could perform any possible computation—using ions of multiple elements. A universal set of quantum gates is one of the so-called DiVincenzo criteria (see http://arxiv.org/pdf/quant-ph/0002077.pdf), which describe the elements needed to build a practical quantum computer.

NIST's new mixed-atom gates could also help make better simulators to model quantum systems and could enable faster and simpler measurements in applications such as NIST's experimental quantum logic clock.

The mixed-atom gates rely on NIST's technique for entangling ions demonstrated more than a decade ago. Multiple carefully tuned laser beams apply an oscillating force to a pair of ions. If the ions are in different internal states, they feel different laser forces that alter the ions' external motions. This coupling of internal states with external motions has the effect of entangling the ions.

More information: T.R. Tan, J.P. Gaebler, Y. Lin, Y. Wan, R. Bowler, D. Leibfried, and D.J. Wineland. 2015. Multi-element logic gates for trapped ion qubits. *Nature*. Dec. 17. nature.com/articles/doi:10.1038/nature16186

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